General background on storm surge

Pat Fitzpatrick and Yee Lau
Mississippi State University

Storm surge is an abnormal rise of water associated with a cyclone, not including tidal influences

Low pressure system can be a baroclinic cyclone, tropical cyclone, or a hybrid of the two.

Fundamental surge components

- Pressure setup - *increase in water level due to lower atmospheric pressure in storm interior.* A slight surface bulge occurs within the storm, greatest at the storm's center, decreasing at the storm's periphery. For every 10-mb pressure drop, water expands 4.0 inches.
  - *Effect is a constant*

- Wind setup - *increase in water level due to the force of the wind on the water.* As the transported water reaches shallow coastlines, bottom friction slows their motion, causing water to pile up. Further enhanced near land boundaries.
  - *Depends on bathymetry, size, and intensity. MOST IMPORTANT IN TERMS OF MAGNITUDE FOR SHALLOW WATER BATHYMETRIES!*

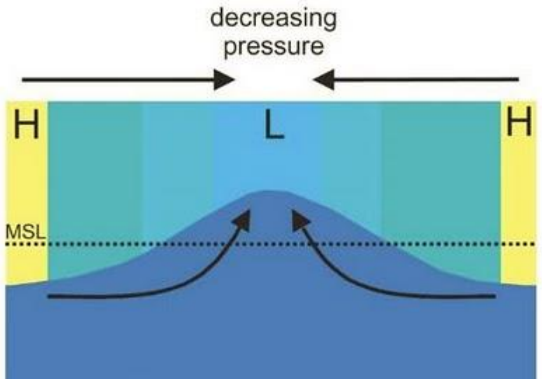
- Geostrophic adjustment – *water levels adjust to a developing longshore current.*

  - *Impact increases for slow-moving tropical cyclones*
  - *Impact increases for larger tropical cyclones*
  - *Causes a storm surge "forerunner"*
  - *Generally second in importance. Impact varies with bathymetry slope and intensity*

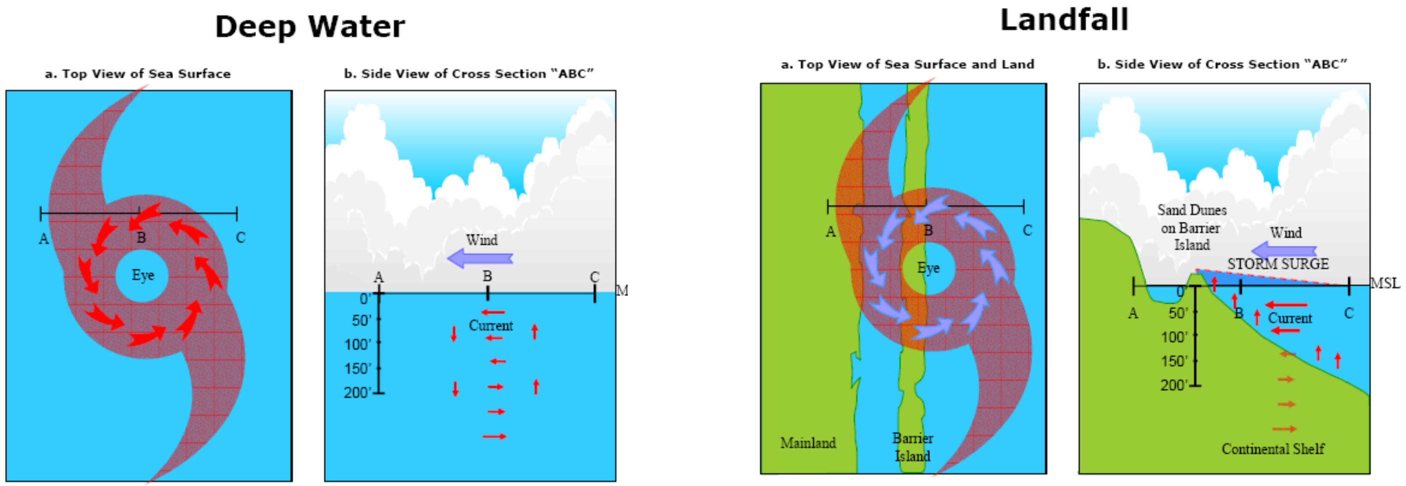
- Wave setup - *increase due to onshore waves.* Incoming water from wave breaking exceeds retreating water, resulting in water accumulation.

  — *Impact minor in shallow bathymetry; may be most important in deep bathymetry (still the subject of research)*

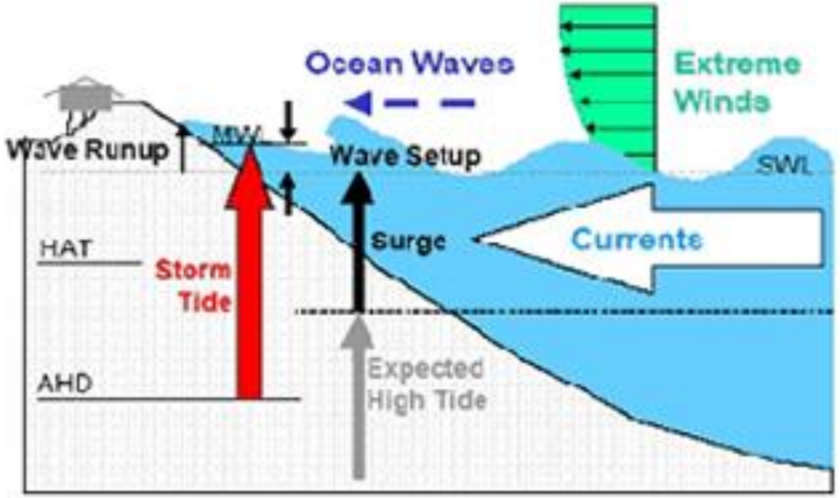
Pressure setup



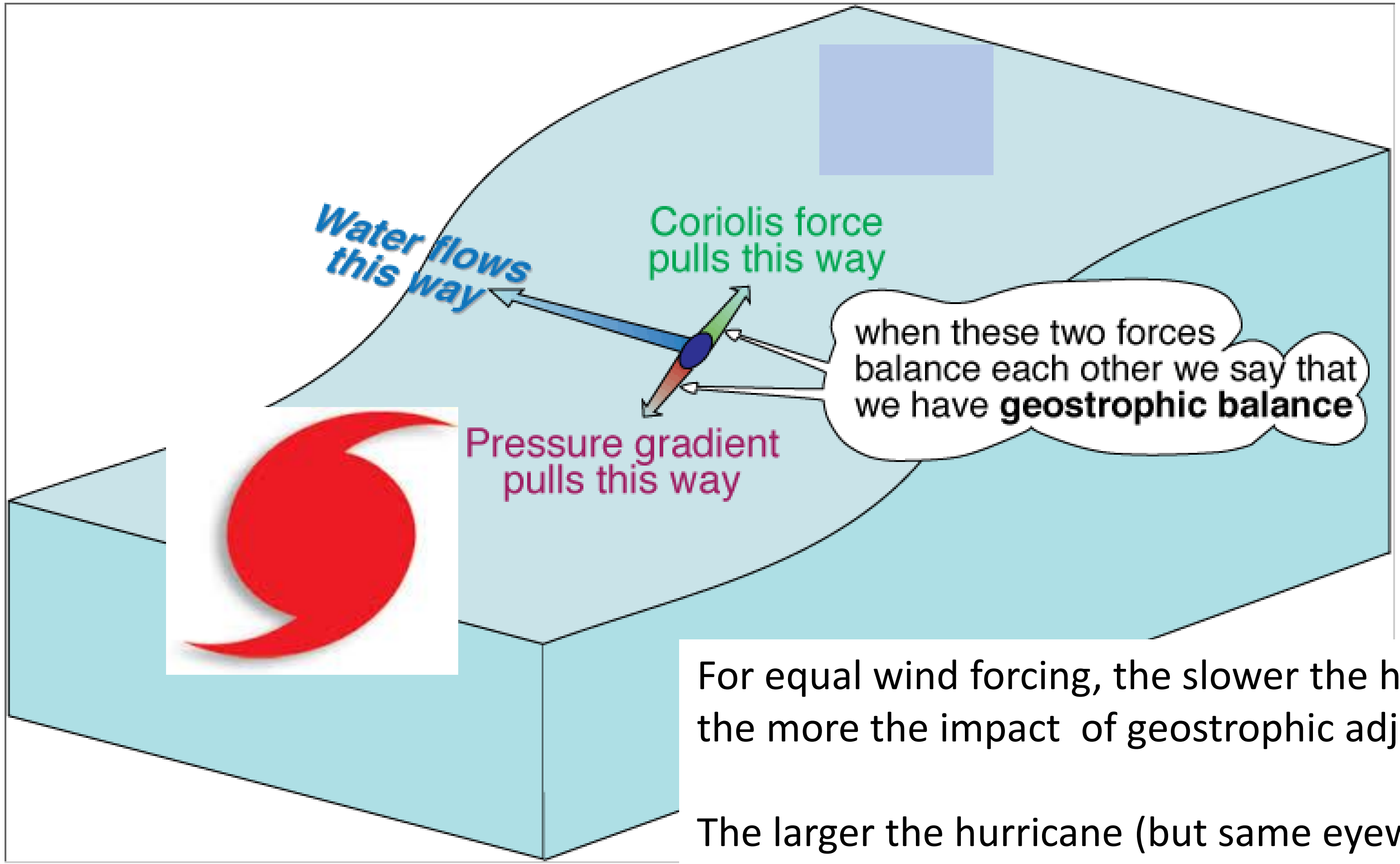
Wind setup



Wave setup



Geostrophic adjustment (creates surge "forerunner")



The balance between pressure gradient forces and Coriolis forces on a parcel

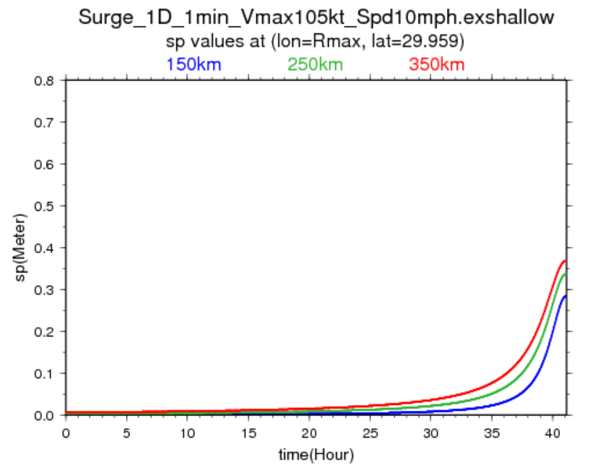
For equal wind forcing, the slower the hurricane moves, the more the impact of geostrophic adjustment on surge

The larger the hurricane (but same eyewall wind magnitude), the more the impact of geostrophic adjustment on surge (Fitzpatrick et al. 2012)

http://www.seos-project.eu/modules/oceancurrents/oceancurrents-c06-s02-p01.html

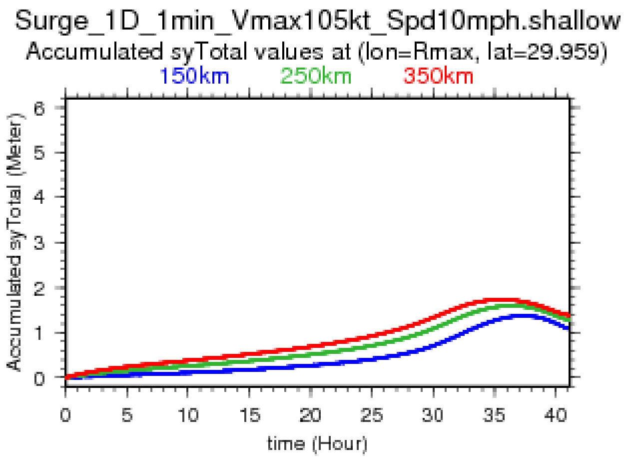
Pressure effect

(peaks at landfall)



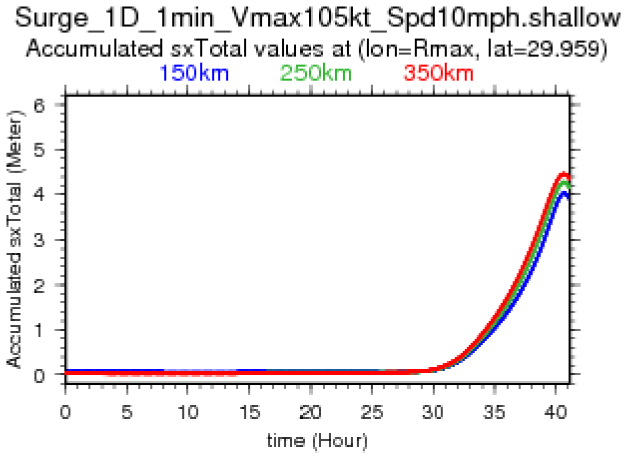
Surge forerunner

(peaks before landfall)



Wind effect

(peaks at landfall)



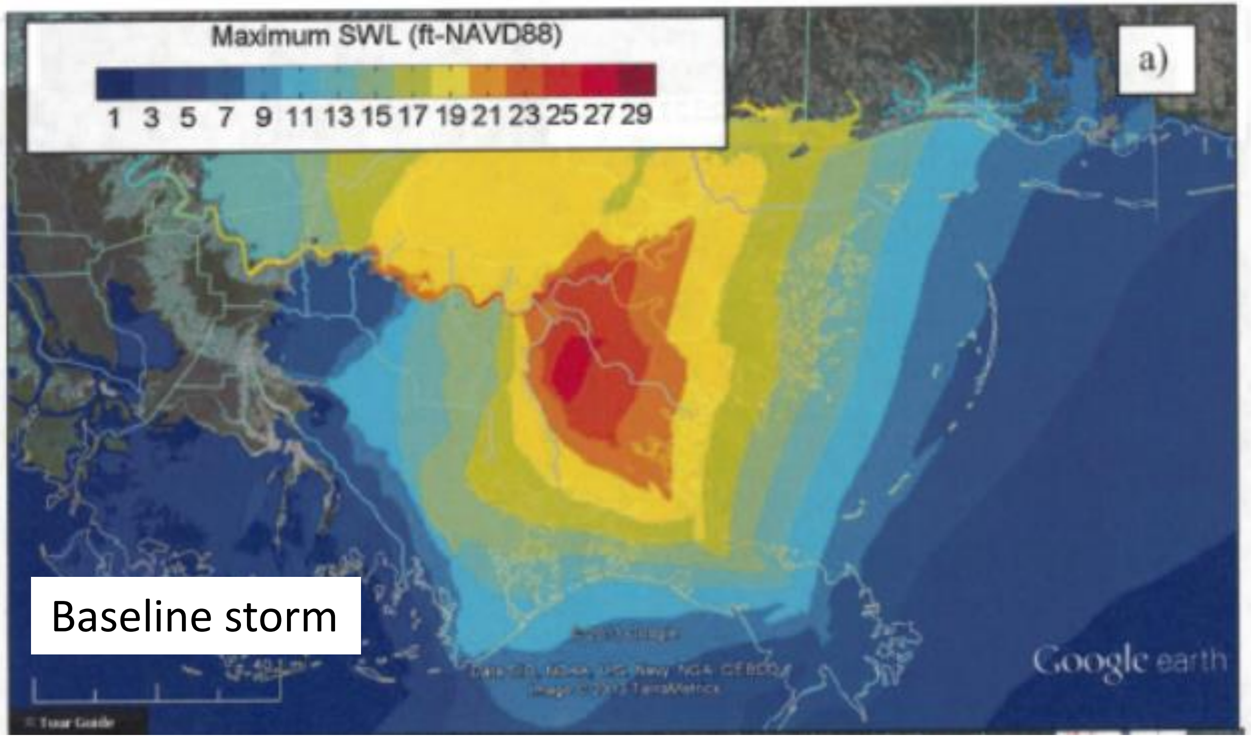
Time series example for Cat 3 in shallow bathymetry for small, average, and large hurricane moving 10 mph

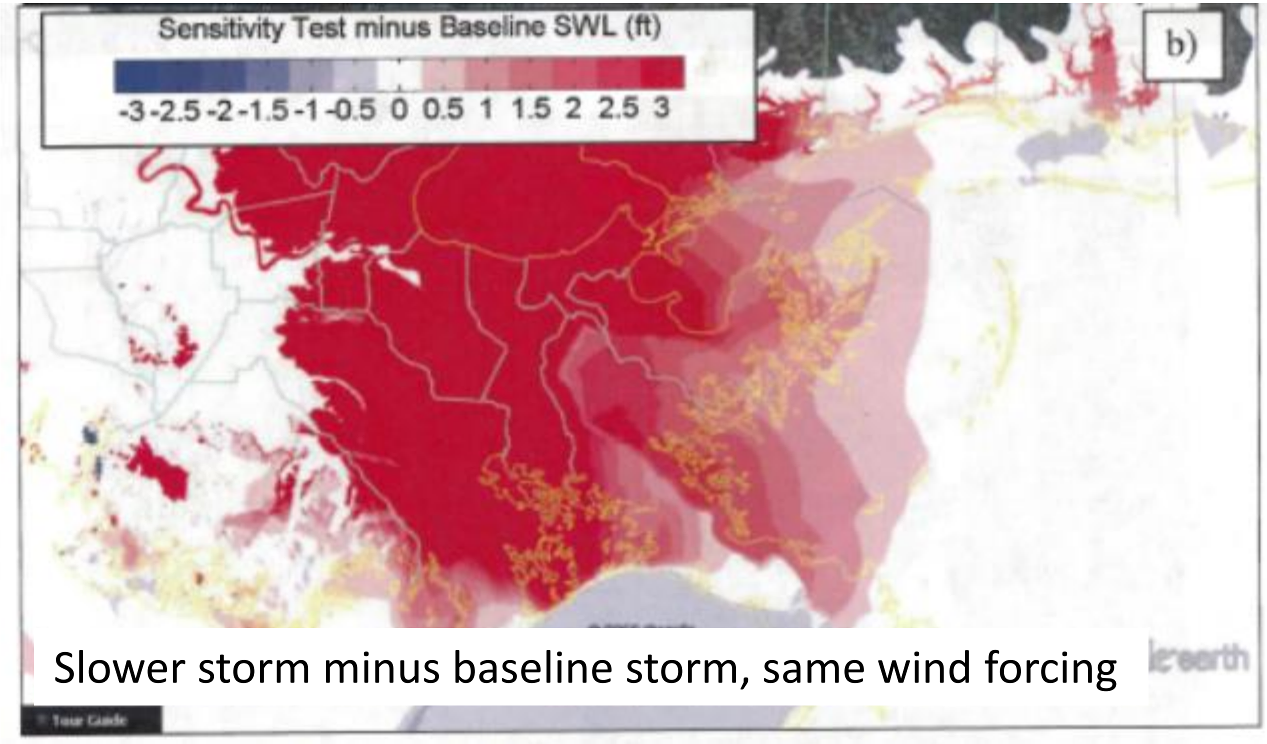
Surge on coastline

“Size” dictated by radius of 34 knots winds

Eyewall winds same magnitude

Comparison average speed versus slow storm
Tropical cyclone making landfall in Terrebonne Bay, LA



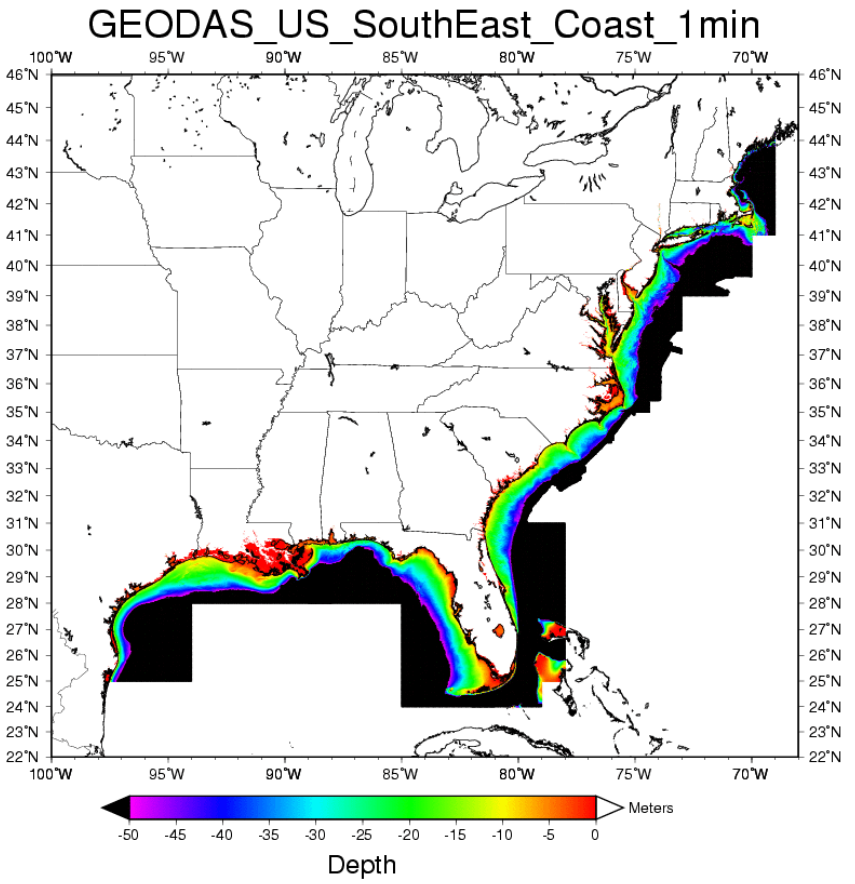


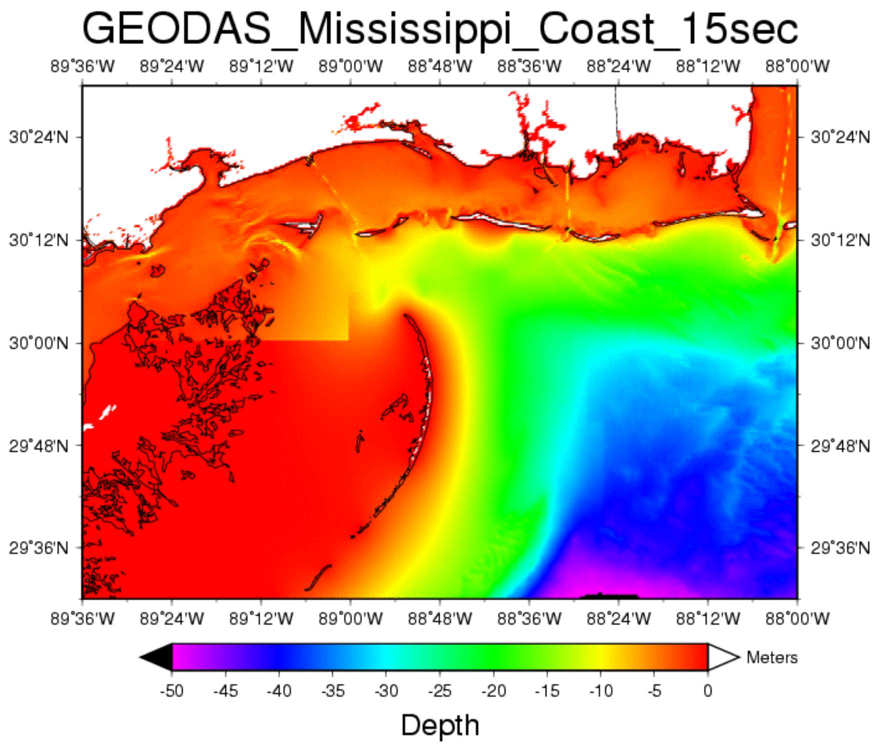
For the exact same spatial wind stress, slower storms produce higher surge

Other components for consideration

- Tide
- Steric setup – (water expansion or contraction as function of water temperature, small)
- Nonlinear advection (small, neglected in SLOSH, optional in ADCIRC)
- Dissipation terms
- ADCIRC has rudimentary river hydrology, SLOSH does not

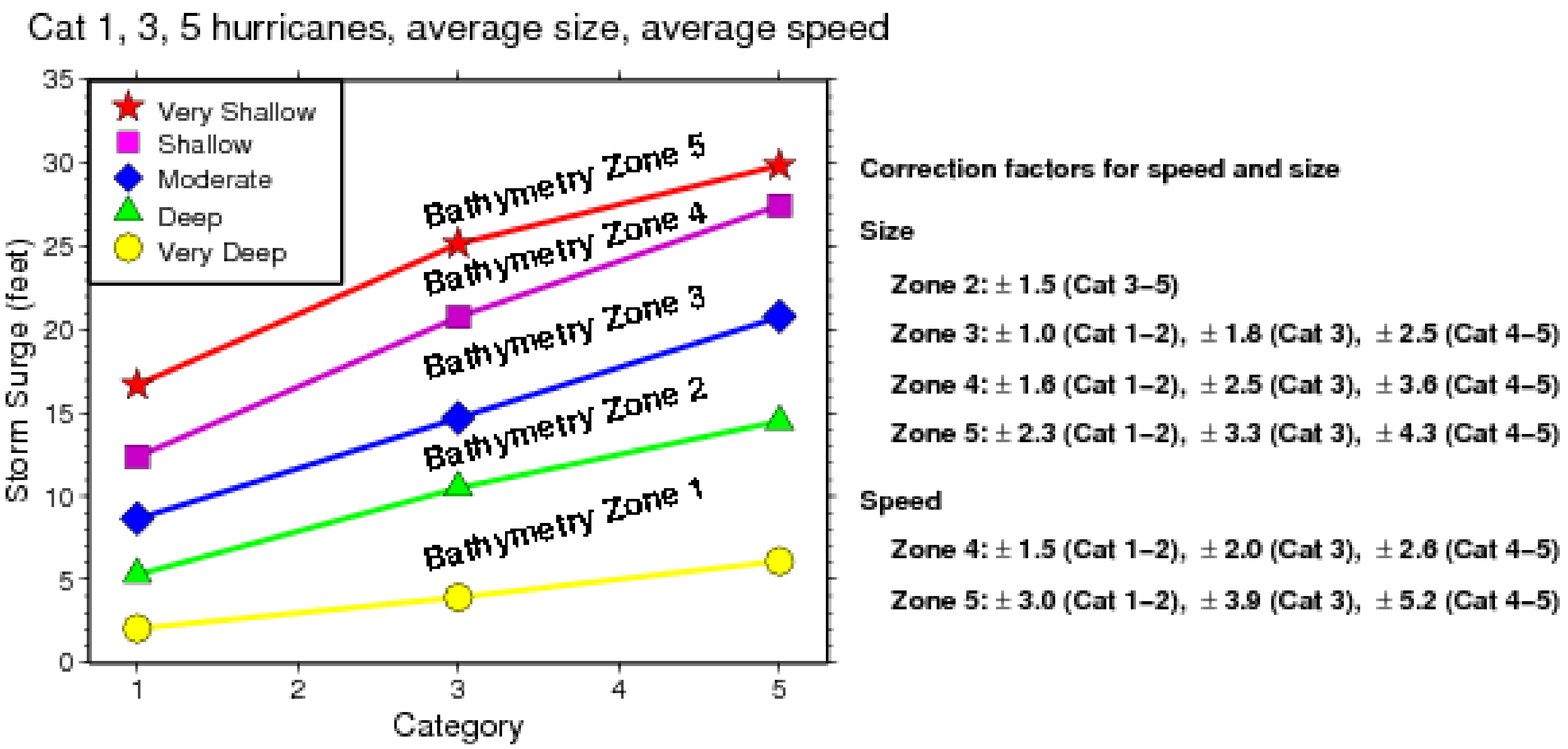
Surge varies due to different bathymetries and boundaries





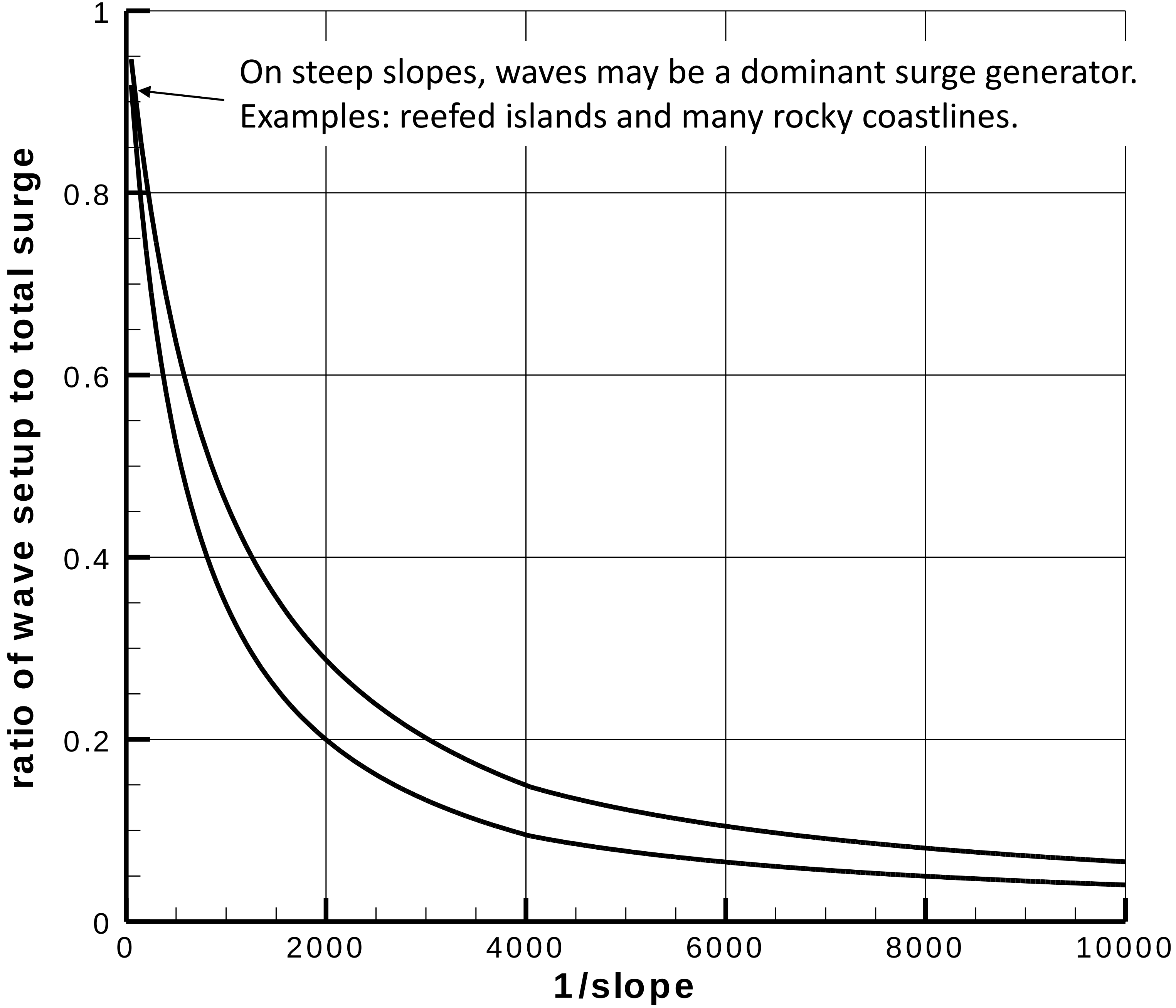
Thought question --- where would surge be worse for a major hurricane?

Effect of hurricane intensity, size, and speed on storm surge



Scale validated against storm surge database, Fitzpatrick and Lau 2011

Estimated relative contribution of waves to total surge



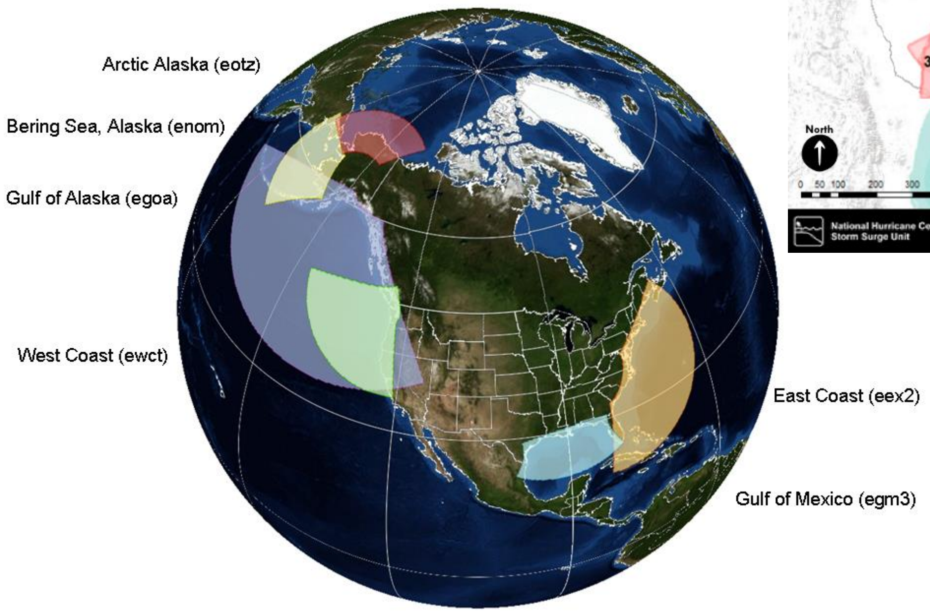
Resio (2012)

Overview on ADCIRC, SLOSH, and other storm surge models

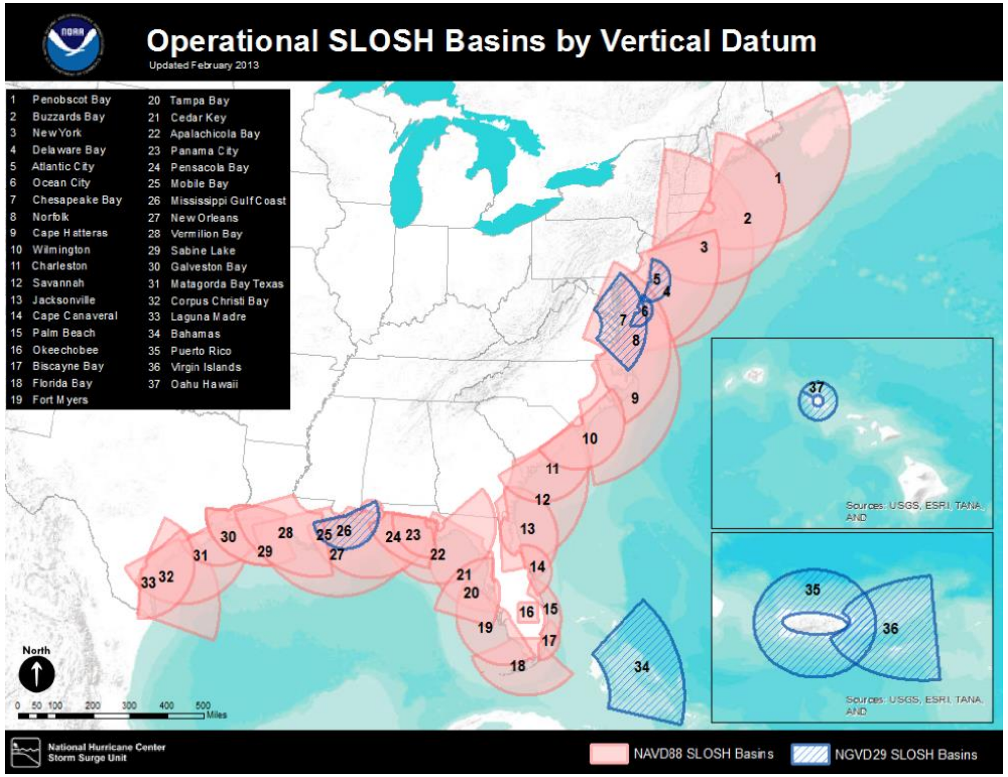
Figures courtesy of Dr. Rick Luettich (University of North Carolina) and Arthur Taylor at NOAA's Meteorological Development Laboratory (MDL)

SLOSH

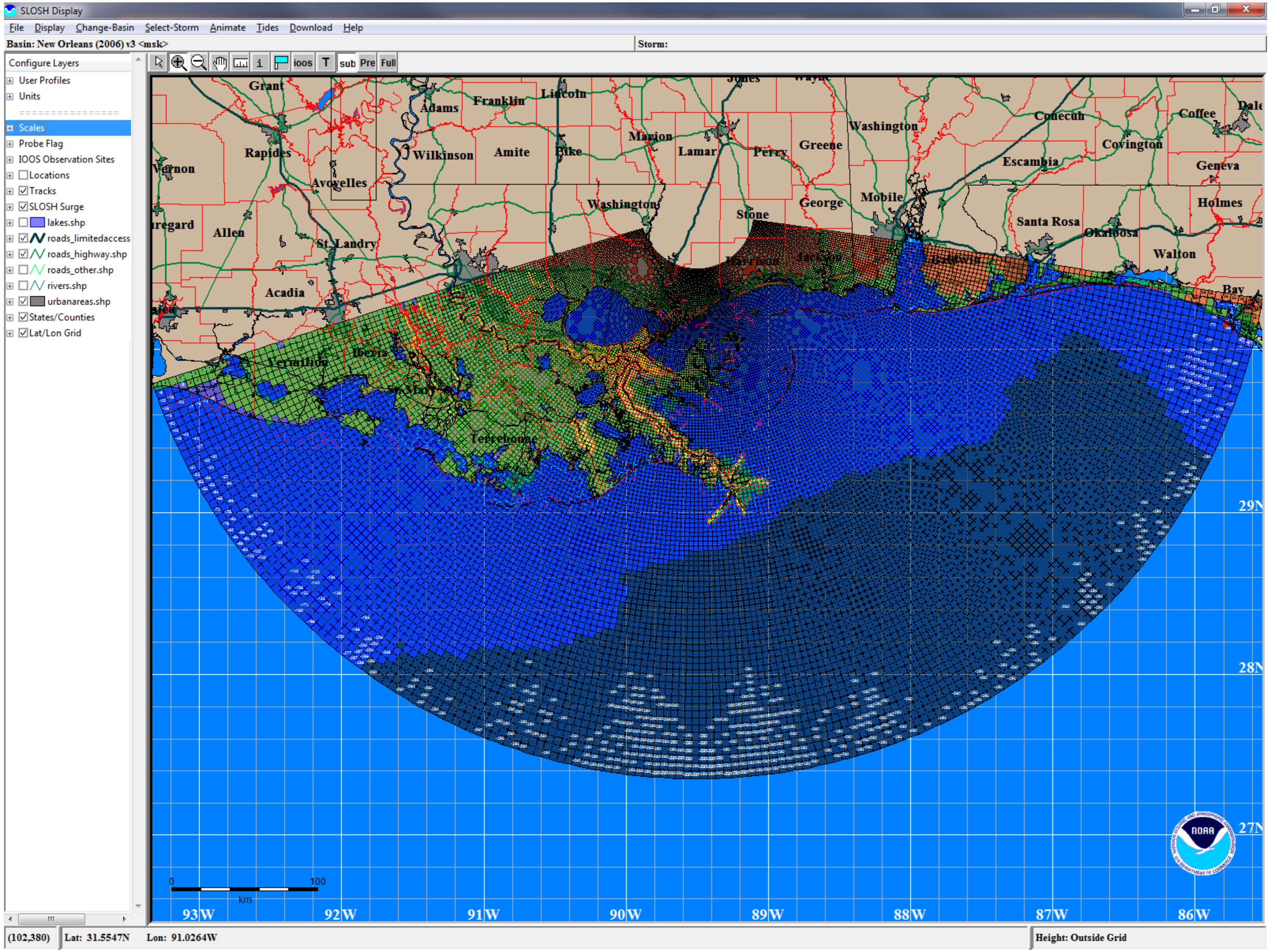
SLOSH Basin
National Coverage



Extratropical Storm Surge Computational Areas



Louisiana basin



SLOSH is the official NOAA storm surge model

- ❑Has to run quickly and reliably
- ❑Has to use operational computational resources
- ❑Inputs are tied to official NHC forecast
- ❑Has to have national coverage

- ❖Finite differencing model with overland flooding developed by NOAA MDL to predict storm surge
- ❖Computationally efficient (ran on DOS in the 1980s)

- Input
  - Track => NHC advisory
  - Current Rmax => estimated from available obs
  - Current DelP => NHC Advisory
  - Forecast Rmax, DelP => estimated by NHC's storm surge specialists

Note that wind is not input. The wind is computed from a pressure field.

The emphasis is on computations speed and the ability to run many simulations based on possible track, intensity, speed, and size errors.

A family of tracks is used to forecast surge probability operationally.

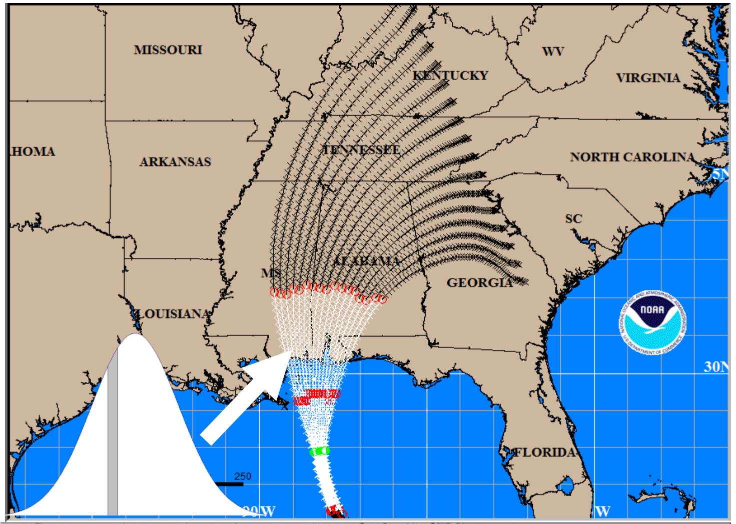
For hurricane evacuation planning, the ability to easily generate thousands of simulations also provides worse-case scenario guidance.

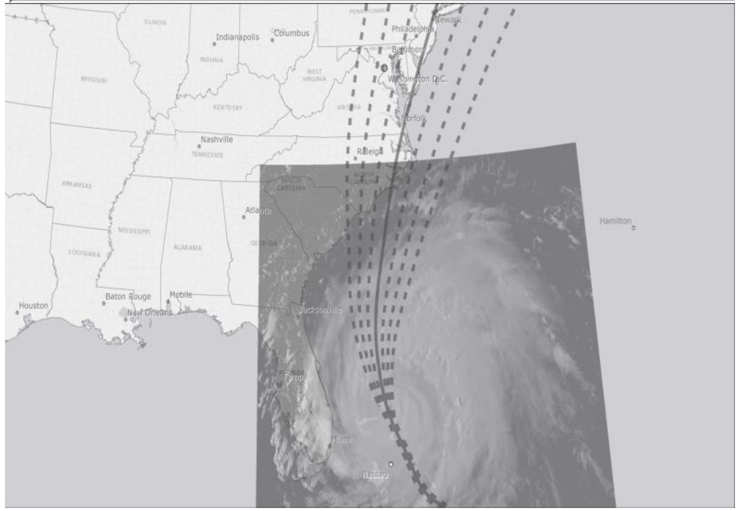
What is P-Surge?

A suite of products that satisfy the need for **P**robabilistic storm **Surge** information within 1 hour of the advisory

- Derive probabilistic guidance from a set of Sea Lake and Overland Surges from Hurricanes (SLOSH) model runs
  - Ensemble centered on NHC's official advisory
  - Error spaces (except size) defined by a normal distribution with 5-y MAE = 0.7979 sigma
  - Error space sampled via representative storms

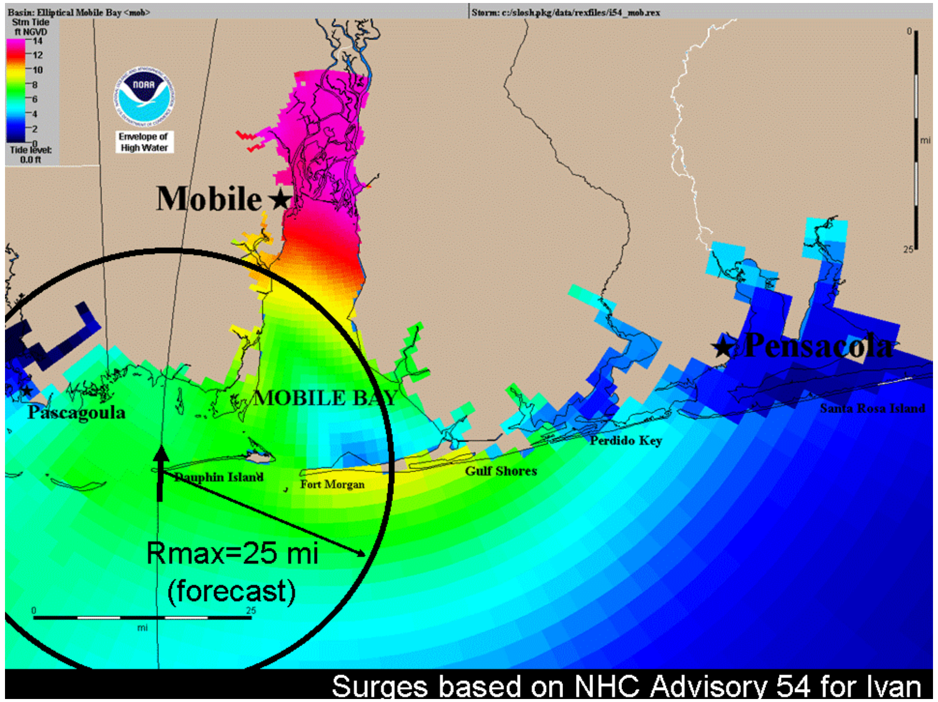
- Why SLOSH?
  - Efficient (100s of runs with relatively few CPU)
  - Maintained as part of hurricane evacuation studies
  - Parametric wind model for forcing
  - Overland flooding

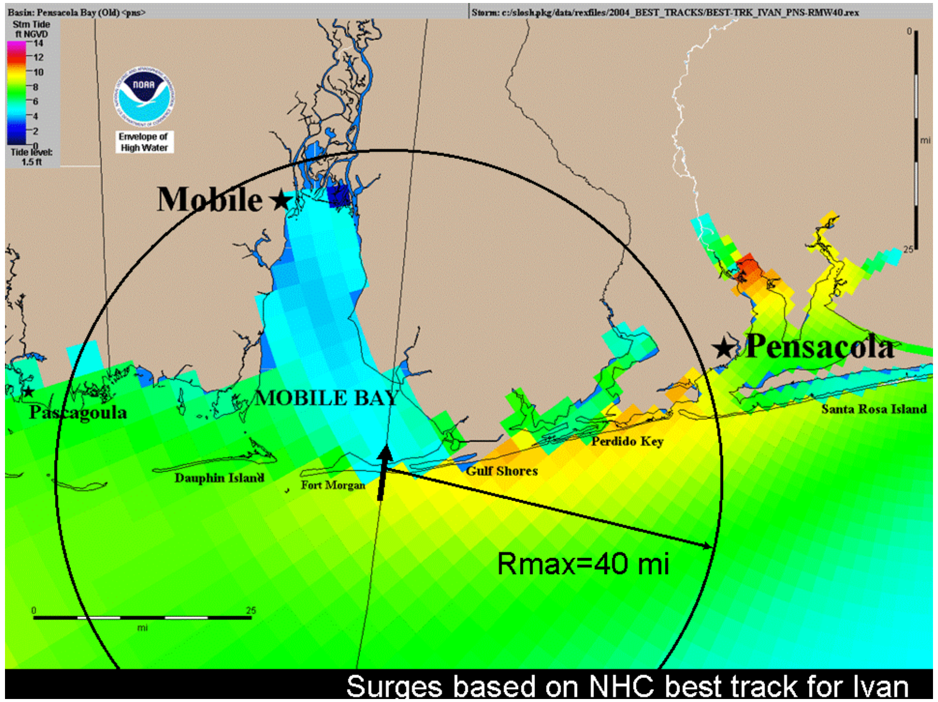




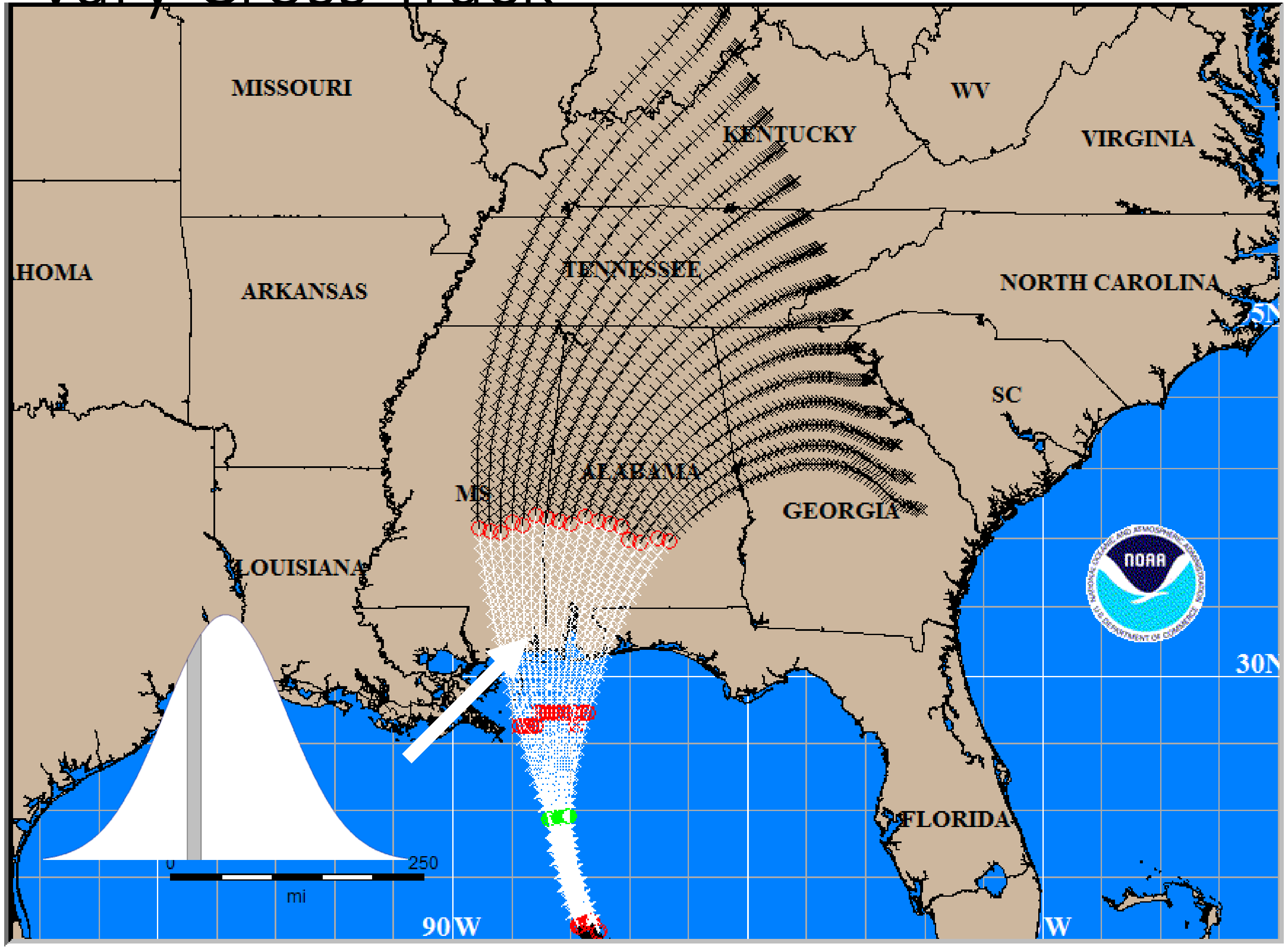
Ivan Adv54
12h before landfall

The major errors in storm surge forecasts are due to the input wind forecast.

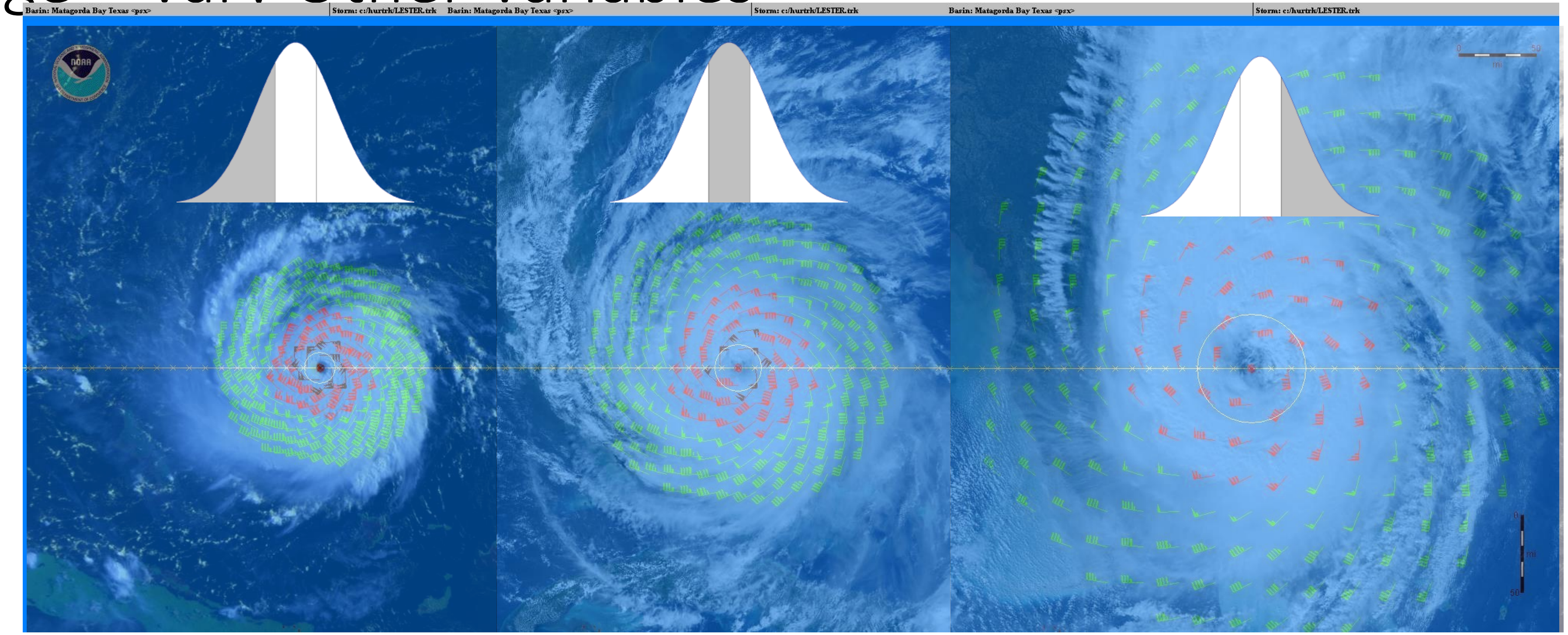




P-Surge - Vary Cross Track



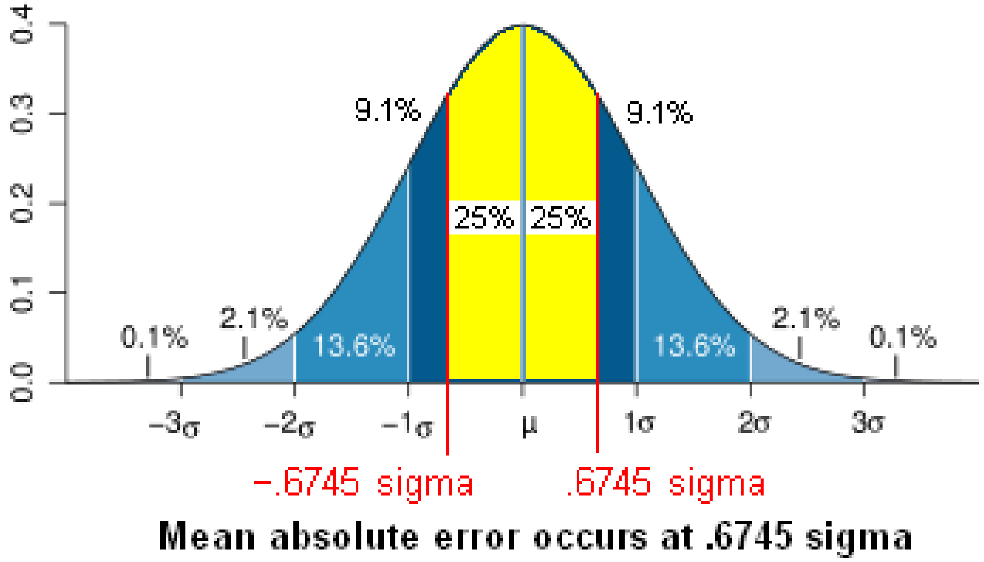
P-Surge – Vary Other Variables

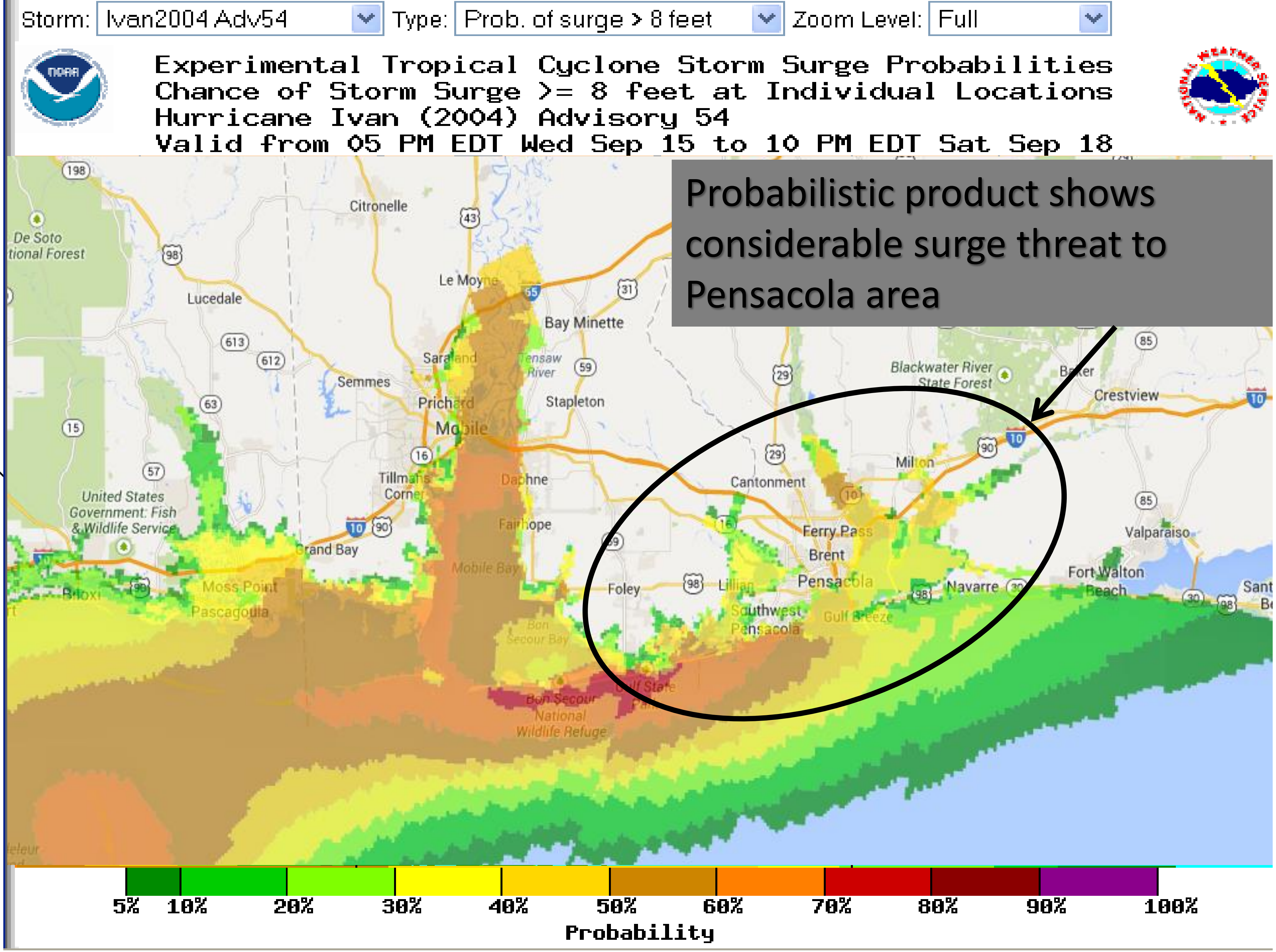


- Size: Small (30%), Medium (40%), Large (30%)
- Forward Speed: Fast (30%), Medium (40%), Slow (30%)
- Intensity: Strong (30%), Medium (40%), Weak (30%)

P-surge Error Distributions

- Error distributions are computed for cross track, along track and intensity by:
  - Assuming a normal distribution
  - Using a 5-year "mean absolute error" and getting the standard deviation (sigma) from:

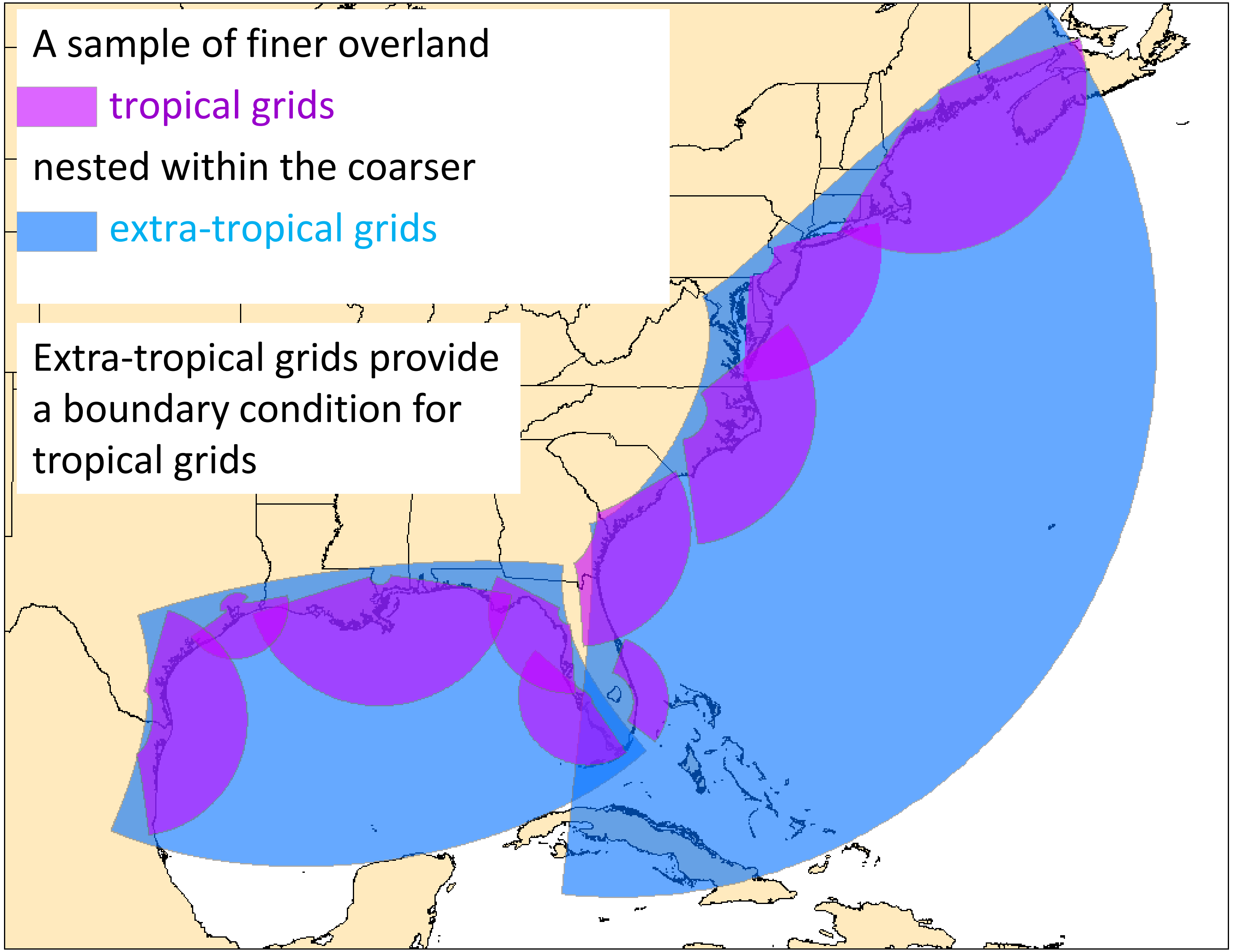



Storm: Ivan2004 Adv54
Type: Prob. of surge > 8 feet
Zoom Level: Full
Experimental Tropical Cyclone Storm Surge Probabilities
Chance of Storm Surge >= 8 feet at Individual Locations
Hurricane Ivan (2004) Advisory 54
Valid from 05 PM EDT Wed Sep 15 to 10 PM EDT Sat Sep 18
Probabilistic product shows considerable surge threat to Pensacola area
Citronelle
Le Moyne
Lucedale
Bay Minette
Saraland
Semmes
Prichard
Mobile
Stapleton
Daphne
Tillmans Corner
Fairhope
Grand Bay
Mobile Bay
Moss Point
Pascagoula
Biloxi
Foley
Cantonment
Milton
Ferry Pass
Brent
Pensacola
Lillian
Southwest Pensacola
Gulf Breeze
Navarre
Crestview
Valparaiso
Fort Walton Beach
Blackwater River State Forest
Bon Secour National Wildlife Refuge
United States Government: Fish & Wildlife Service
5% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Probability

Extra-Tropical Storm Surge (ETSS)

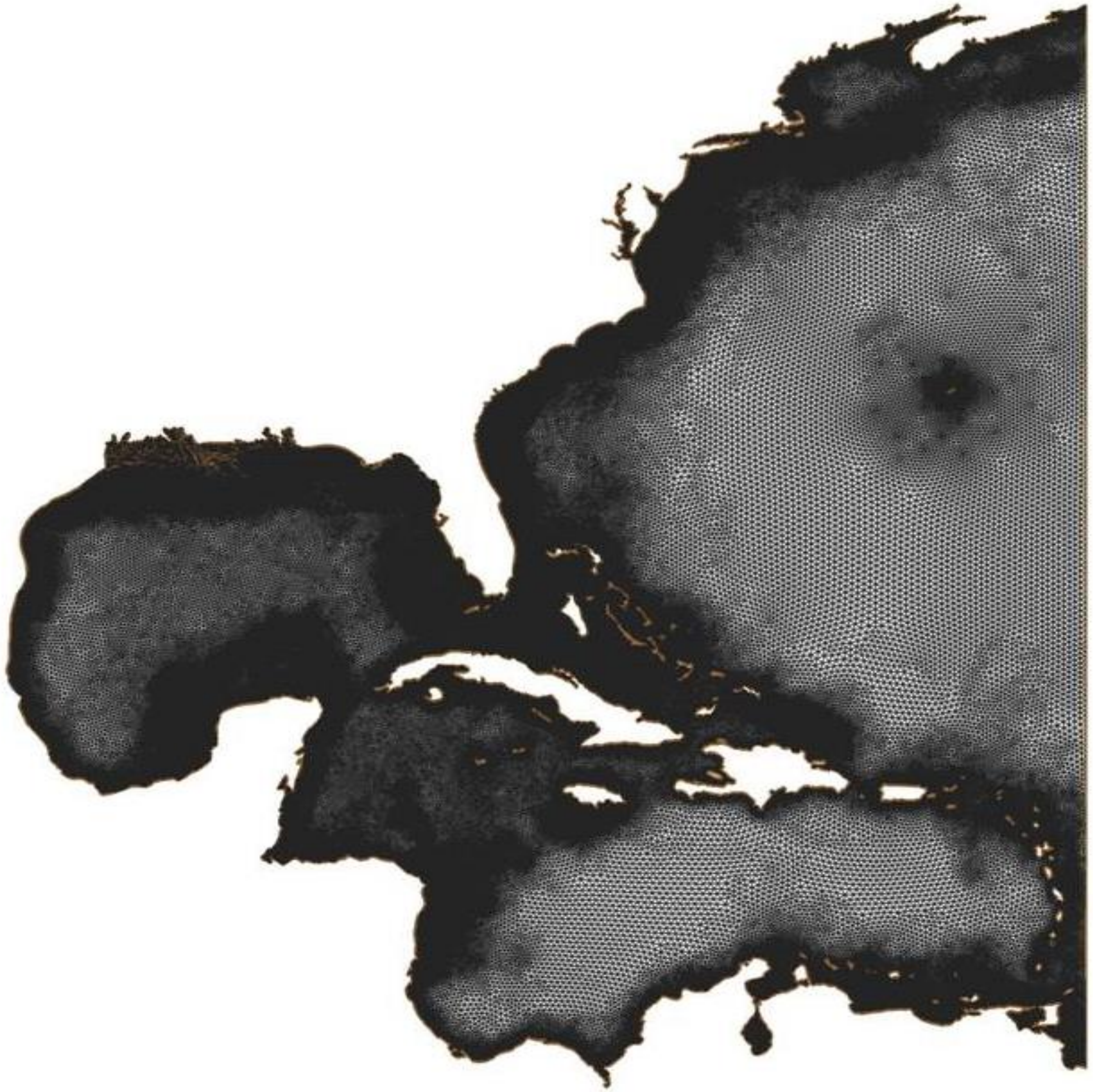
- Modification of SLOSH to use 0.5 degree Global Forecast System (GFS) winds and pressure as input
- Intended for large extra-tropical storms rather than hurricanes (aka tropical storms)
- Does not include Waves and River Flow
- It's been applied to
  - Bering, Beaufort, Chukchi Seas, AK (Oct 2015)
  - Gulf of Alaska (Apr 2008); West Coast (Feb 2011)
  - East Coast (Feb 2009); Gulf of Mexico (Jan 2011)

ETSS 2.0 – Nest coarse and fine Grids for East Coast and Gulf of Mexico



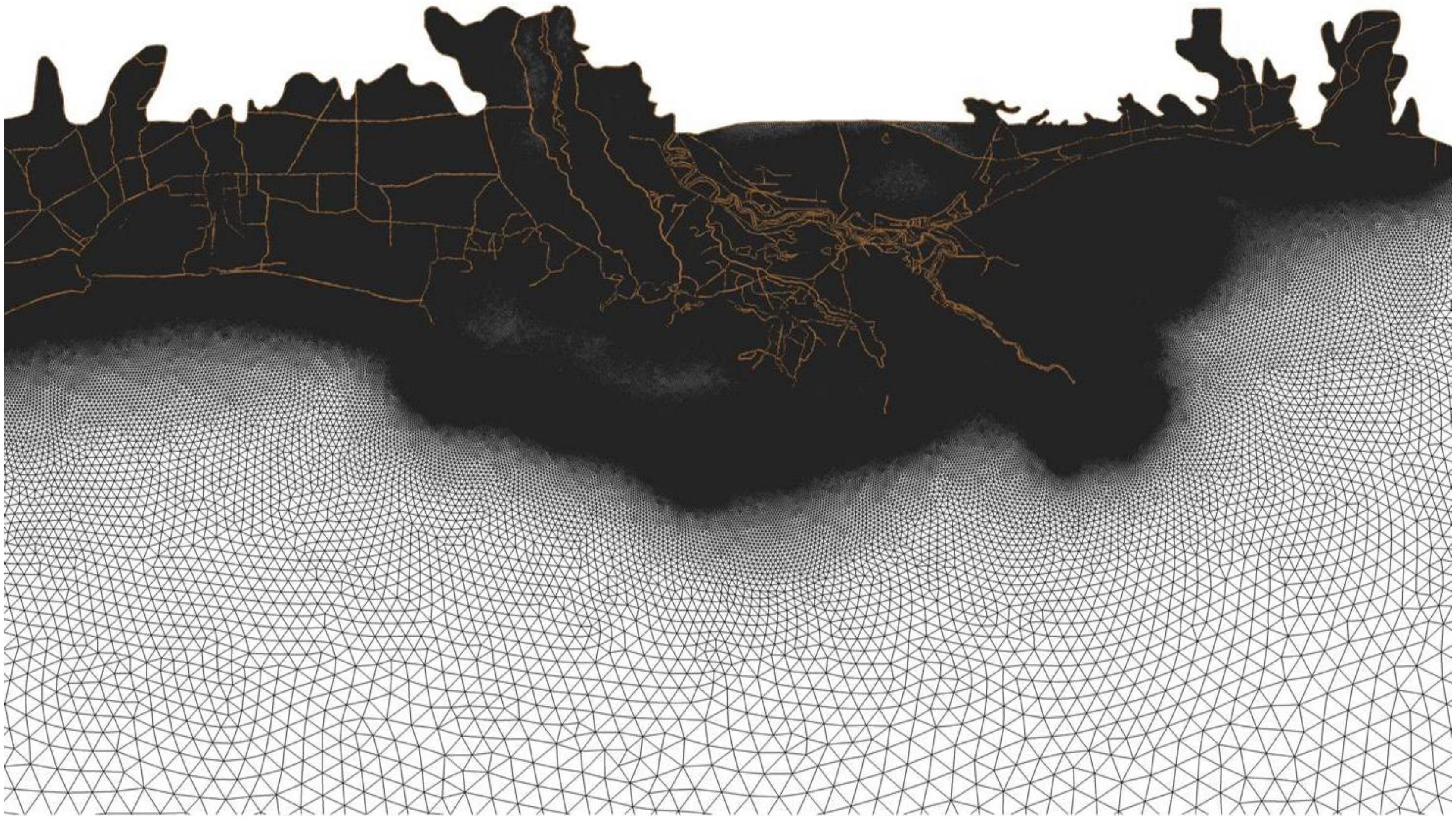
ADCIRC

Typical ADCIRC background grid

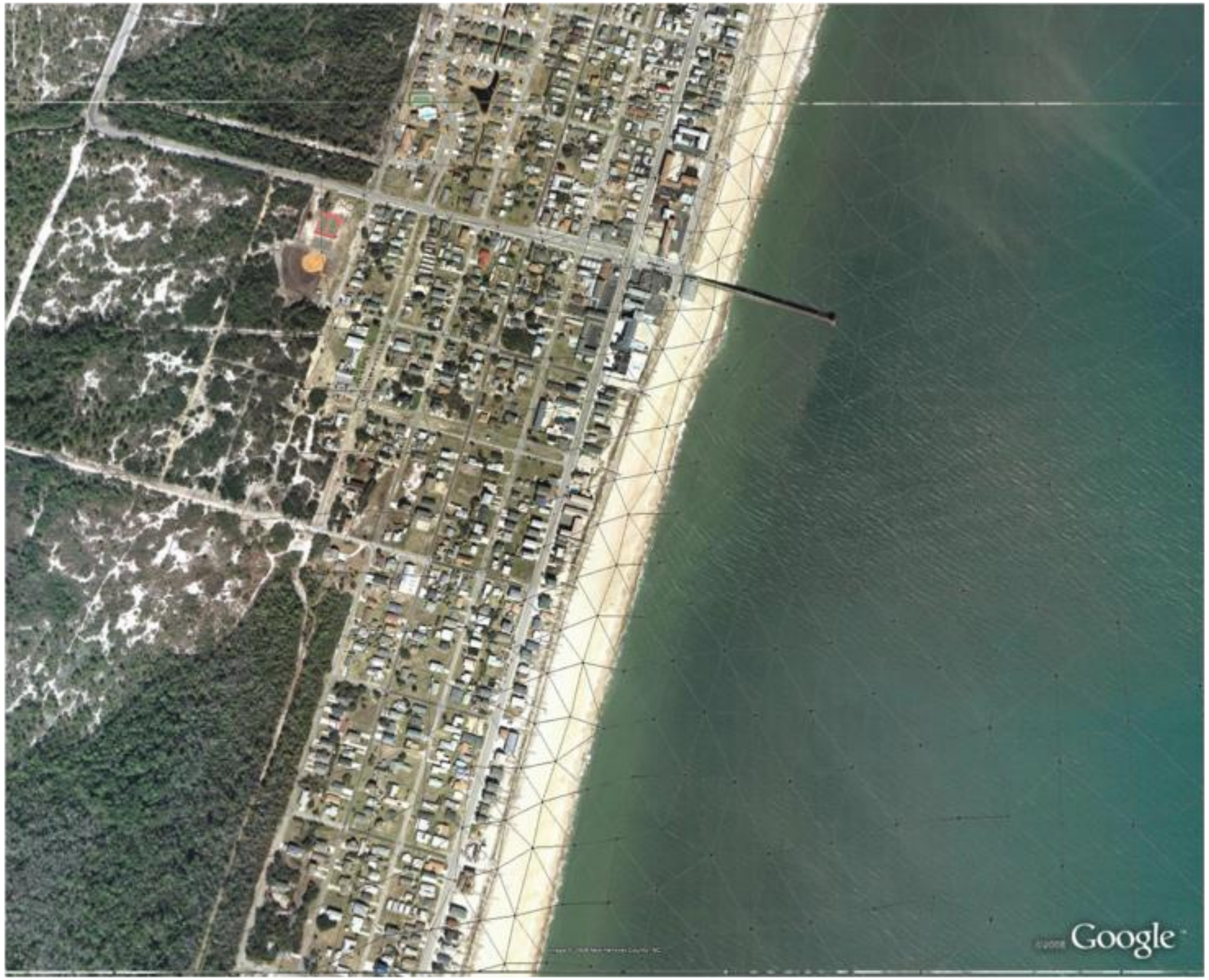


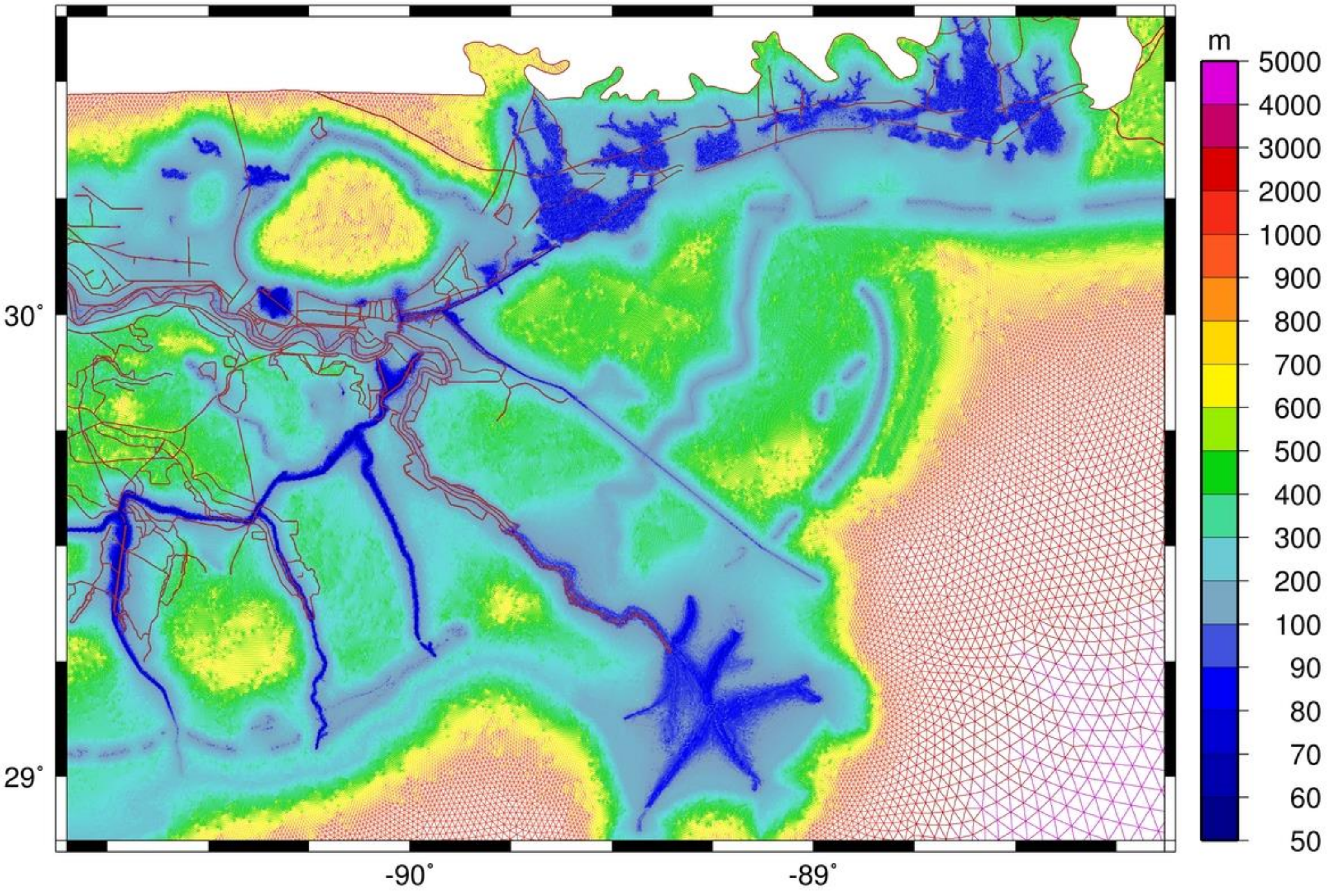
There is a very high-resolution grid imbedded in the baseline grid along different sections of the US coast

Example ADCIRC grid along LA and MS coast



20-30 meters along immediate coastlines



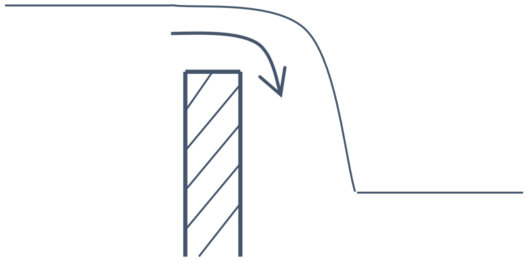


30˚
29˚
-90˚
-89˚
m
5000
4000
3000
2000
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50

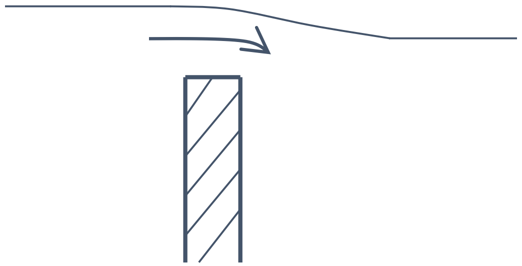
Sub-Grid Scale Features in ADCIRC mimic control structures and levees

Broad Crested Weirs

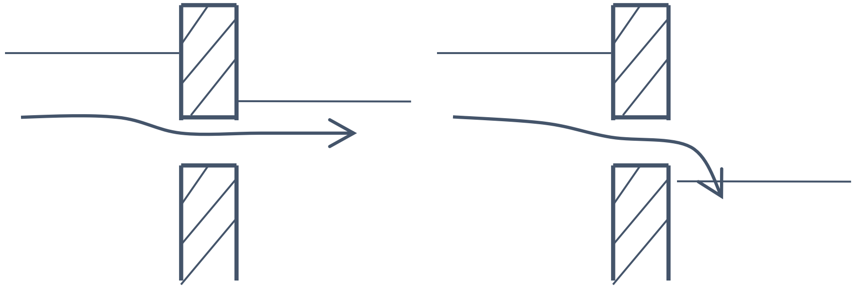
Critical Flow

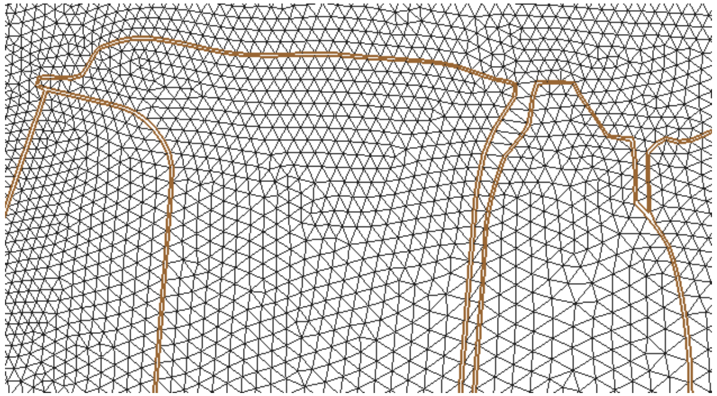


Sub-critical Flow



Culvert/submerged openings





ADCIRC in Coastal Hazard Assessment

Post storm forensic assessments

- Detailed information in space and time
- Case studies

FEMA National Flood Insurance Program

- All coastal states from NY to TX
- Most studies performed by USACE or private sector

Nuclear Regulatory Commission

- Coastal nuclear power plants
- Private sector consortium

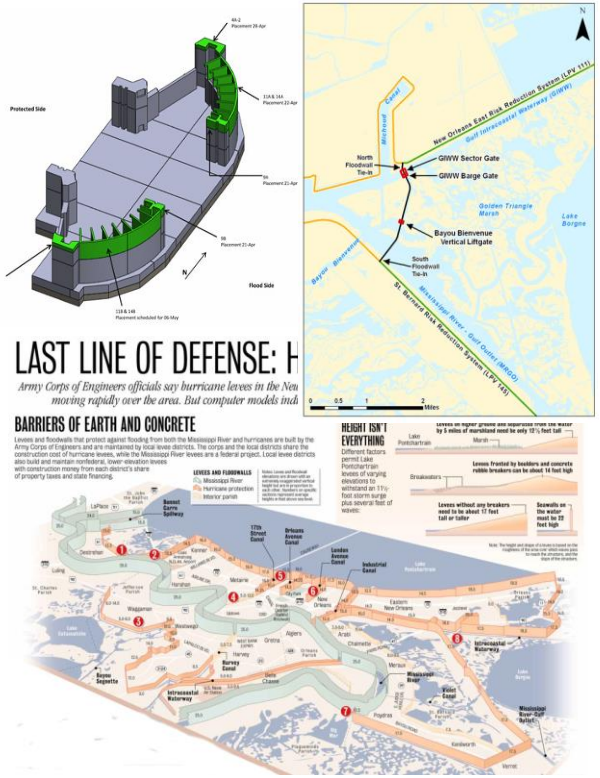
Louisiana Master Plan

- Land loss and land building

ADCIRC in Coastal Risk Reduction

Infrastructure Design

- $14.5 Billion Hurricane Storm Damage Risk Reduction System around greater New Orleans after Katrina
- Mayor Blumbert’s $20B storm damage reduction plan for NY City area following Hurricane Sandy
- Ike Dike and associated strategies in the Houston – Galveston area



ADCIRC in Forecasting

- ADCIRCs require significant computing resources
- NOAA EMC is running ADCIRC for extratropical storms
- For the first time, in 2016 NOAA EMC is running ADCIRC for tropical cyclones when track and intensity forecast is high. This is called the Hurricane Surge On-Demand Forecast System.
- A GUI interface called the ADCIRC Surge Guidance System (ASGS) is used by LSU, UNC, and in the private sector.
- WorldWinds runs ADCIRC based on NHC forecast and for 2-3 alternatives
- In general, multiple operational runs in operational forecasting is not possible with ADCIRC due to computational limits, even on massively parallel supercomputers.